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AUTONOMOUS VEHICLE SYSTEMS: IMPLICATIONS FOR MARITIME OPERATIONS, WARFARE CAPABILITIES, AND COMMAND AND CONTROL

by

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Military operations within the last decade have seen enormous growth in the fielding and utilization of unmanned tele-operated vehicles in the air, ground, and maritime domains. With advances in computing and processing technology, these vehicles and systems are becoming increasingly autonomous in nature and will continue to evolve in the future, significantly impacting the warfighter and the battlespace.

A great deal of research and development (R&D) is currently underway by the Department of Defense (DoD), as well as in industry and academia, in the field of autonomous systems. As the technology in this area rapidly advances, comparatively little is known about how these systems will affect our future organizational and Command and Control (C2) architectures, or their implications for the future of warfare in general. This thesis catalogues the current and emerging technologies associated with these systems, within the context of the capabilities they bring to the warfighter. From this baseline, an analysis of future capabilities is conducted against selected maritime operations as identified in the Navy Tactical Task List (NTTL). Impact to organizational performance is analyzed using the Congruence Model, and possible implications are drawn about the near-term future of naval operations and organizational change.

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LIST OF ACRONYMS AND ABBREVIATIONS

AO	Area of Operations
AVS	Autonomous Vehicle System
AUV	Autonomous Underwater Vehicles
BLOS	Beyond Line-of-Sight
C2	Command and Control
CONOPS	Concept of Operations
COP	Common Operational Picture
CTF	Combined Task Force
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DOTMLPF	Doctrine, Organization, Training, Material, Leadership, Personnel, Facilities
EOD	Electronic Ordnance Disposal
EOIR	Electro-Optical Infrared
GPS	Global Positioning System
HMI	Human Machine Interface
ISR	Intelligence Surveillance and Reconnaissance
JCA	Joint Capability Area
JCIDS	Joint Capabilities Integration and Development System
LIDAR	Light Detection and Ranging
LOS	Line-of-Sight
MCM	Mine Countermeasures
MIPS	Millions of Instructions Per Second
MIW	Mine Warfare
MOE	Measures of Effectiveness
MOC	Maritime Operations Center
NAVCENT	Naval Forces Central Command
NMETLs	Navy Mission Essential Task List
NTTL	Navy Tactical Task List
NTA	Navy Task

ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
OTH	Over the Horizon
PEO LMW	Program Executive Office for Littoral and Mine Warfare
RADAR	Radio Detection and Ranging
R&D	Research and Development
RMA	Revolution in Military Affairs
SA	Situational Awareness
SATCOM	Satellite Communications
SPAWAR SSC	Space and Naval Warfare Systems Center
UAS	Unmanned Aircraft System
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
USCC	Unmanned Systems Common Control
UUV	Unmanned Underwater Vehicle
UVS	Unmanned Vehicle System

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I. INTRODUCTION

A. OVERVIEW

The rapid, widespread, and relatively recent introduction of advanced Unmanned Vehicle Systems (UVS) into the modern operating environment has greatly impacted how the U.S. Armed Forces is planning for and conducting its various missions. UVS, particularly within the air domain, have become mature and preferred assets to the operational commander for missions such as persistent Intelligence, Surveillance, and Reconnaissance (ISR), as well as limited strike opportunities. The preference for these systems is quickly transitioning to dependence on them as UVS continue to evolve in capability and versatility.

A major aspect of that evolution is the trend toward system autonomy. As computer programming and processing technology continues to advance, the capability of these systems to operate independent of direct human control is expanded greatly. This autonomous capability will continue to develop in the future, as the Department of Defense (DoD) invests ever-increasing sums of money and resources in the field. Numerous Research and Development (R&D) efforts are currently underway within the department, industry, and academia aimed at solving the complex problems associated with system autonomy and robotics capability. Service and individual agency strategy documents, Concept of Operations (CONOPS), and master plans are beginning to address autonomy as a necessary and desirable attribute of future UVS. The Department recognizes that these systems will take on an even greater role in the future battlespace environment.

Automation of commercial and military related tasks has been an ongoing, incremental progression for much of the past century as technology has continued to drive innovation and organization productivity. Utilizing machine automation for relatively simple, mundane tasks releases other assets and resources and allows for streamlining of organization business processes. Automation of modern military related operations and tasks however, with their inherently dangerous and dynamic nature, is

exceedingly more complex and requires certain levels of machine awareness and decision making capability. Continuing to remove the human from both the non-kinetic, and eventually kinetic, missions and tasks suggests an impending revolution in military affairs. Modern UVS, like those so favored in Iraq and Afghanistan, represent the next step toward system autonomy and artificial intelligence that can not only perform simple military related support tasks, but entire mission sets. The continued development and fielding of these advanced systems into the dynamic operating environments the U.S. military will likely find itself in the future implies major changes in how we train, organize for, and execute our missions.

B. PROBLEM STATEMENT AND RESEARCH QUESTIONS

While the technologies and associated capabilities of autonomous vehicle systems (AVS) continue to progress rapidly, comparatively little is known about how these systems will impact the future operating environment. Likewise, incorporating truly autonomous, intelligent systems into existing organizational structures and Command and Control (C2) architectures has not been fully explored. Technology is once again ahead of appropriate guidance and doctrine for effective utilization. While this thesis does not intend to provide detailed guidance for the employment of future AVS, it does aim to identify implications and gain insight into how these systems will impact our warfighting ability and organizational structures. Thus, this research will seek to answer the following questions:

- How will the rapidly emerging technologies and capabilities associated with advanced AVS affect the future of C2 and organizational structures and how will they need to evolve, particularly within the maritime environment?
- How will the future of information superiority and decision making be affected by intelligent, and potentially collaborative, AVS?

C. METHODOLOGY

This research will provide background into the current state of unmanned and autonomous systems development and employment in the air, ground, and maritime domains. In addition, it will identify the necessary features and components that comprise modern AVSs, as well as document some expected technological advances and associated capabilities they bring to the warfighter. Analysis of major DoD strategy documents, master plans, and R&D efforts provides the framework for future system capabilities expected to available to the warfighter within the next 10 years.

With a set of expected capabilities identified, analysis focuses on future system employment in the maritime domain. Review of the Navy Tactical Task List (NTTL) reveals operational mission sets that are likely to be impacted heavily by the introduction of advanced AVSs. Analysis of common performance metrics across mission sets provides a means to quantify the necessary basic capability of a future system to achieve mission success in any context. These mission sets are further analyzed against the future technologies and associated system components those technologies will support in the accomplishment of mission related tasks.

This research goes on to present a model for the study of organizational performance and then applies that model to the introduction of advanced AVSs to the maritime operating environment. The model lays out a framework for understanding of organizational dynamics as related to performance and can be used as a methodology for implementation of change. A short vignette is presented to further illustrate the capability realized in an operational scenario. Finally, implications are drawn about the nature of future warfare and organizational impact as a result of intelligent, autonomous systems.

D. SCOPE

A broad survey of UVS and AVS development and employment identifies what is possible with these systems in current military operations. Further review of strategic level guidance reveals the expected roles these systems might fill in the future, and how they are expected to support the warfighter. Analysis is maritime domain/operations

specific and limited in timescale to expected technology readiness and capability delivered within the next decade. The impact of AVS on tactical and operational level information and decision superiority is explored, along with how naval organizational structures would need to change to best capitalize on emerging capability.

Although this thesis aims to layout a framework of future implications, discussion of autonomous employment of firepower and the governing of lethality will not be explored. The complex legal and ethical problems associated with this aspect of machine automation still require detailed national level policy analysis and review. Likewise the incorporation and complete integration of highly intelligent AVS into multiple joint warfare operating constructs is not a topic of this research.

E. ORGANIZATION OF THESIS

Chapter II provides background and literature review into the current state of unmanned and autonomous vehicle employment within the DoD. The recognized organizational impacts of unmanned vehicles, as well as current capabilities and limitations of AVS, also are described. Chapter III establishes the necessary components of AVS, and develops a set of expected future near-term capabilities based on current applied research efforts. From this baseline, an analysis of future autonomous capability is conducted against selected maritime operations as identified in the NTTL. From the study of what is scientifically possible as well as what is likely possible in the near-term, Chapter IV will analyze the impact of machine autonomy to the Navy as an organization. Chapter V provides implications and recommendations for future research.

II. LITERATURE AND TECHNOLOGY REVIEW

A. UNMANNED SYSTEMS

Each service component within the DoD recognizes the need to further harness and integrate the capabilities and value that UVS are bringing to the warfighter. Chief of Naval Operations (CNO) Admiral Gary Roughead, in a recent speech given at the Brookings Institution in Washington, stated that it is imperative upon the Navy to invest in and field unmanned technologies and capabilities that best augment existing platforms (The Brookings Institution, 2009). Further, it is imperative that the Navy continues to develop new operating concepts with these systems in mind. These imperatives are true for all the services, as evidenced by the endorsement of a DoD capstone strategy document for unmanned systems integration.

1. DoD Unmanned Systems Integrated Roadmap

In April 2009, the Office of the Secretary of Defense (OSD) published the FY2009–FY2034 Unmanned Systems Integrated Roadmap. The purpose of this capstone document was to provide strategic guidance and vision for integrating and capitalizing on the various unmanned technologies being provided to the warfighter. The Roadmap recommends unmanned technologies and capabilities to pursue that best support the accomplishment of the Department's goals and missions, with specific focus on how future unmanned investments must be interoperable and supportive of the warfighter (OSD, 2009).

The document describes the current state of UVS within the air domain, within the context of their proven capability to perform persistent ISR missions in support of traditional forces, as well as their ability for dynamic re-tasking across the battlespace as needed by the Joint Force Commander (JFC) (OSD, 2009). Some larger unmanned aircraft systems (UAS), such as the RQ-4 Global Hawk and MQ-9 Reaper, can operate beyond line of sight (BLOS), allowing the remote pilot and sensor operator to control the vehicle from bases in the United States, outside the operating environment. These larger

UAS, with advanced onboard sensors and satellite communications links, are employed in theater ISR as well as limited strike roles on targets of opportunity. A variety of smaller UAS, such as the RQ-11 Pathfinder Raven and RQ-7 Shadow, are rapidly being employed at the tactical (Brigade, Company, and Platoon) level, providing short-term line of sight (LOS) ISR capability. The document acknowledges the relative lead in technology development and employment within the air domain, and thus is focused somewhat on the integration and investment of these systems in particular. Figure 1 depicts the RQ-11 Pathfinder Raven UAV.

Figure 1. RQ-11 Pathfinder Raven UAV (From OSD, 2009)

Unmanned ground vehicles (UGVs) also provide tactical commanders with increased mission capability, while at the same time reducing risk to personnel. Since the beginning of combat operations in Iraq and Afghanistan, some 6,000 UGVs have been procured and deployed in theater conducting missions ranging from reconnaissance for infantry and support units to Improvised Explosive Device (IED) defeat (OSD, 2009). An example of one Program of Record (POR) UGV currently deployed is the Man Transportable Robotic System (MTRS), MK 4 Explosive Ordinance Disposal (EOD). Research into employing UGVs in a variety of other roles including combat casualty evacuation and Chemical, Biological, Radiological, Nuclear (CBRN) detection is currently ongoing.

Within the maritime domain, the Navy is continuing to research and employ Unmanned Underwater Vehicles (UUVs) as well as Unmanned Surface Vehicles (USVs)

that enhance the concepts of fleet transformation and force multiplication. UUVs present a unique opportunity to conduct remote coastal surveillance as well as mine countermeasure missions, while USVs are envisioned conducting maritime ISR as well as port security functions.

2. Organizational Impact of Unmanned Vehicles

Unmanned systems are beginning to impact every aspect of Doctrine, Organization, Training, Material, Leadership, Personnel, and Facilities (DOTMLPF) analysis. DOTMLPF is intended to support the Joint Capabilities Integration and Development System (JCIDS) process. JCIDS aims to identify, and then help field, critical capabilities required by warfighters across all the services to support national security as well as DoD missions and objectives (CJCS, 2009). As UVS technologies rapidly advance, policy and doctrine are catching up in the form of tailored CONOPS, master plans, and employment guidance from operational commanders.

Regardless of technology, one of the most critical assets any organization can possess and leverage is its people. Unmanned systems are changing the way we train and use our personnel within the organization, as is evidenced by the introduction of specialized designators, ratings, and job qualifications. Until recently, for example, the Air Force used traditionally trained aviators to pilot their quickly emerging UAS fleet. Now, however, the service has implemented a non-traditional UAS pilot training program for officers, and a new sensor operator pipeline for enlisted personnel. Unmanned systems courses also have been added to the curriculum at the academy. Intelligence, maintenance, and logistics support personnel will continue to be sourced from traditional units for the time being. These measures are intended to create a "normalized UAS culture" throughout the organization (USAF, 2009). The Air Force has realized the need to embrace UAS as an inevitable and beneficial part of its future, and thus ease the burden of large-scale organizational change.

In addition to training, doctrine, and personnel changes, UVS continue to consume a larger piece of each service's budget with every passing fiscal year. It can be argued that the DoD in particular is an organization driven by budgeting of ever-

increasing scarcity of funds. The fact that the DoD roadmap, as well as subordinate service strategy documents, calls for increasing investment of precious dollars in research and development—as well as procurement of unmanned systems—implies change in organizational priorities and thinking.

B. FROM UNMANNED TO AUTONOMOUS

UVS have provided a means of removing human operators from direct contact with potentially dangerous situations within the battlespace. As established, these systems are conducting single-mission tasks traditionally performed by military personnel. They remain however, remotely supervised and directly controlled by humans, using existing communication architectures and data links. In a presentation on Mission Focused Autonomous Control in June 2009, Dr. Bobby Junker of the Office of Naval Research (ONR) stated that one of the primary factors driving systems development in this field is the desire to effectively automate information analysis and interpretation, as it is a manpower-intensive activity. Limited over-the-horizon (OTH) and LOS tactical communications, as well as the need for unmanned systems to perform multiple mission tasks in dynamic battlespace environments, are among other factors.

In general terms, autonomy is defined as “the quality or state of being self-governing” (autonomy, n.d.). Within the realm of unmanned systems, however, a more specific definiton is necessry. At the 2003 Performance Metrics for Intelligent Systems Workshop, Huang, Messina, and Albus defined unmanned systems autonomy as “its own capability to achive its mission goals” (Huang, Messina & Albus, 2003). They further stated that the more complex the mission goals are, the higher the level of autonomy required, and that levels of autonomy are proportional to the system’s capability to percieve, plan, decide, and then act.

An AVS can also be separated into the physical vehicle itself, be it an air, ground, or maritime variant, and the associated sensor hardware and computer software the vehicle relies on to conduct its mission(s). Depending on that mission, combinations of Global Posistioning System (GPS), Electro-Optic Infrared (EOIR), Milimeter Wave (MMW), and Light Detection and Ranging (LIDAR) are examples that make up the

"sesnsor package" that the vehicle uses to establish its postion, navigate itself and identify its mission objectives. This sensor package is integrated with computer processing hardware and software, as well as communications equipment for relay of information or possibly coordination with other vehicles/units. The vehicle itself is merely a transport mechanism for the autonomous sensor package, placing the sensor in the most ideal position within the battlespace for mission accomplishment. The integration of the sensor package with the physical vehicle is what makes an autonomous system a potential force multiplier.

1. Current State of Autonomous Systems Within DoD

The Air Force Unmanned Flight Plan outlines the necessary requirements, capabilities, and enabling technologies of current and future UAS within the context of DOTMLPF synchronization to achieve desired future levels of autonomy (USAF, 2009). It is the intent of the Air Force to incorporate UAS autonomy in the near-term where it increases the overall effectiveness of the platform and where it best supports the warfighter and/or decision maker. Ongoing efforts at the Air Force Research Lab (AFRL) and Air Force Institute of Technology (AFIT) are comprised of GPS-based autonomous navigation to achieve automated in-transit flight as well as automated launch and recovery. Employment testing is being conducted using existing UAS platforms such as the RQ-11 Raven and the MQ-1 Predator, among others.

Research into utilizing small- to medium-sized UAS in a *swarm* configuration is also ongoing. The concept of *swarming* calls for a group of several semi-autonomous aircraft connected to each other by a wireless ad-hoc network. The swarm would be monitored by a single human operator and be employed in direct support of both manned and unmanned units, conducting imagery and sensor analysis, threat identification, and persistent ISR of the battlespace (USAF, 2009). Individual aircraft within the swarm would also have the ability to conduct airspace management and obstacle aviodance with one another. Future autonomous capabilities include air-refueling, airlift, and stratigic strike.

Autonomous ground vehicle development is focused in the areas of navigation, obstacle avoidance, and "sense making" within challenging terrain as well as urban environments. For example, in 2007, the Defense Advanced Research Projects Agency (DARPA) hosted a competition called Urban Challenge, which brought together teams from industry and academia in an experimental setting. The teams were required to modify existing vehicles to negotiate various forms of complex urban traffic conditions. For the first time, autonomous vehicles successfully interacted with both manned and other unmanned vehicle traffic for a duration of approximately four hours (DARPA Urban Challenge, 2007). Each team's vehicle received an initial uploaded "mission definition/route file" five minutes prior to beginning the event, and this action constituted the extent of human interaction.

As part of Space and Naval Warfare Systems Center (SPAWAR SSC) Pacific's ongoing Urban Exploration Project, advanced autonomous behaviors for navigation, mapping and exploration are being tested on small UVGs within complex, multi-building urban test bed environments. The first round of experimentation, completed in 2008, focused on assessing the vehicle's ability to calculate position without the use of GPS, and to map the inside of structures with high degrees of clutter and obstruction. Utilizing the Autonomous Capabilities Suite (ACS), a modular software architecture integrating specific autonomous behaviors and perceptions with associated onboard sensor devices, SSC's small UGV was able to effectively map, and navigate through, the interior of a one-story building. The vehicle used laser scan matching and video data to build a map of its surroundings and reference its own position within that map with minimal input and correction from the operator.

Current ONR USV efforts are focused on delivering perception-based navigation and maneuvering, on-board health monitoring, and mission level autonomy (Office of Naval Research, 2008). ONR also is developing "clean sheet" USV designs vice modifying existing manned craft. Numerous USVs have demonstrated the ability to conduct autonomous GPS waypoint navigation, and current testing is concentrated on autonomous path planning to achieve dynamic obstacle avoidance of both fixed and mobile contacts as well as terrain features. These vehicles use many of the same sensor

devices that can be found on other UVS such as on board chart libraries, RADAR and GPS inputs, and EO/IR imagery. Figure 2 depicts the USV design under development by ONR.

Figure 2. ONR USV (From Office of Naval Research, 2008)

2. Capability Challenges and Limitations

It is important to note that the concept of "auto-pilot" has been around for decades, and is relatively easy to achieve. Simply recording current heading and position data, a vehicle's computer can then mechanically direct its control mechanisms, such as rudders and propulsion, through the use of actuators. Likewise, current guided munitions utilize fire and forget technology to "autonomously" guide themselves to their targets. These environments are relatively static. What separates "auto-pilot" from intelligent autonomous systems is their ability to make sense of and react within dynamic operating environments given what they "see," and take effective actions to accomplish mission tasks and goals without the need for direct human supervision.

Some of the limitations and challenges associated with current AVS are common regardless of operating domain. As previously mentioned, much research is currently underway in the field of obstacle avoidance and optimum path navigation. Driving by GPS waypoints can be relatively easy, but accomplishing this while simultaneously taking into account trees, buildings, wind speed, altitude, water depth, current, sea state,

and other moving vehicles is somewhat more complicated. Successfully negotiating these conditions while en-route, or while conducting mission tasks and goals, poses a significant challenge to current systems. A human will see and anticipate the effects of sea state conditions on his craft, and take action accordingly. Thus far, a computer cannot accomplish these tasks with a high degree of reliability.

Another limitation associated with current AVS relates to contextual decision making and Situational Awareness (SA) (Finn and Scheding, 2010). Key components of good decision making are an accurate perception, comprehension, and projection of the operating environment, which together make up SA (Finn and Scheding, 2010). Unmanned and semi-autonomous systems still rely a great deal on supervisor and operator injection based on sensor data collected. As of yet, AVS are unable to distinguish uniqueness and complexity with regard to their environment; indeed, they are not aware of what their environment is. A computer makes logical decisions based on its programming and, unfortunately, the modern battlespace does not always afford the decision maker logical or even rational choices. This limitation implies a lack of reliability, adaptability, and agility within the operating environment.

This challenge is further compounded when we take into account the problem of human-autonomous system interaction and collaboration. As of now, humans still interact with semi-autonomous systems in a direct supervisor and guidance role. Much research is currently underway in this area, ONR’s Human-Unmanned Systems Integration and Perception, Understanding, and Intelligent Decision Making initiatives being examples. According to ONR, autonomous systems are meant to be an extension of, and collaborator to, the warfighter. Until these systems can share information and SA, as well as reliably complete mission tasks in such a way that is natural and beneficial to us, they will not achieve their intended role or earn the trust of their supervisors.

C. COMMAND AND CONTROL

The term Command and Control certainly has evolved since its inception more than 60 years ago. With each iterative addition of terms to the original C2 (C3, C4I, C4ISR, etc.), the concept of command and control in modern military

operations has come to encompass a great deal. In its broadest sense, however, the DoD currently defines C2 in Joint Publication 1-02 as:

> The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission. Also called C2. (Department of Defense, 2001)

C2, however, is no longer tied to one single commander at the top of an organization; rather, it is distributed responsibility in modern warfare (Alberts & Hayes, 2003). Therefore, C2 can now also be understood to mean the fusing of technologies, resources, and information with operators and decision makers at all levels of an organization, with the goal of task and mission accomplishment. C2 are functions that need to be accomplished for mission success, and are therefore argued to be about providing the necessary and suficient conditions for that success, and not necessarily how these functions are performed (Alberts & Hayes, 2003).

The conditions for success could be many things, but inherent to them is robust experience, information, and communication flow, shared SA, and task allocation throughout the organization that contributes to decision superirority. Again, the effective use and employment of an organization's assets (both technological and human) is a critical aspect of C2.

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III. OPERATIONAL ANALYSIS

A. FEATURES AND COMPONENTS OF AUTONOMOUS SYSTEMS

In defining AVS for the purposes of this thesis, the physical vehicle as well as the controlling computer software, decision algorithms, and sensor packages are identified as major components that allow the system to conduct its assigned mission. A robust systems engineering and integration process is required when developing an autonomous system and to be sure, many of the components and sub-components are dependent on vehicle mission and operating domain. There are, however, several necessary features and components common in all modern autonomous systems.

In their recent work on AVS, Finn and Scheding (2010) discussed the key functional components in terms of their inter-dependence and integration to form the overall system. The authors identified components of any autonomous system to be combinations of sensor packages, navigation hardware and software, communications equipment, as well as varying levels of human interaction. These components allow for other features and behaviors of the system, and when further coupled with platform specific design and payloads, allow for mission execution. The complete functional relationship diagram is depicted in Figure 3.

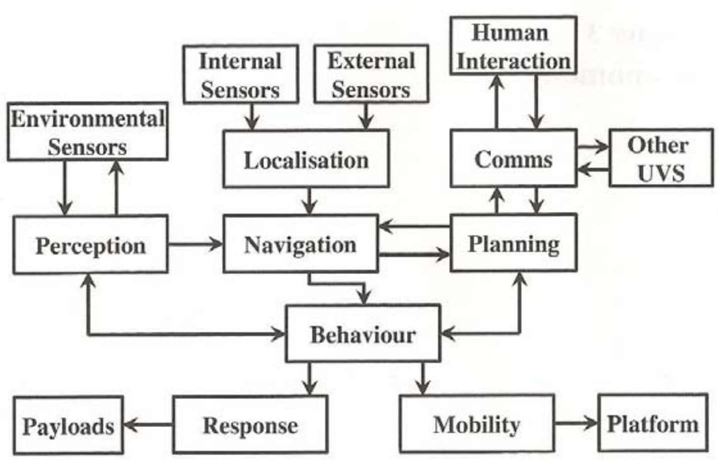

Figure 3. Key functional relationships for an autonomous UVS (From Finn & Scheding, 2010)

The mission payload component is usually composed of sensor packages in many configurations, depending on platform and operating domain. They essentially allow the system to "know" its position and movement relative to some reference, and to perceive mission relevant data necessary for task completion. A few major examples of sensor sub-components include GPS, magnetic compasses, EO/IR cameras, and Radio Detection and Ranging (RADAR). The sensor packages, and the associated behavior they facilitate, are critical to the overall effectiveness of the system in the performance of its mission.

Also common to all systems is some form of communications capability, which allows for collaboration and interaction with human supervisors and/or other unmanned systems. These communication components usually take the form of LOS (HF, UHF, and VLF), satellite communications (SATCOM) data links, or some combination of the two. The communications component present on the vehicle, and on any other vehicles or supervising entities, form the architecture for achievement of shared SA.

Of equal importance to the AVS is the human interaction component. These systems, even if operating at varying levels of autonomy, will always require human input from design inception through employment. Thus, the human interaction piece takes many forms including programmers, engineers, and users/supervisors that design and operate the system (Finn & Scheding, 2010). These systems, to the extent allowed by technology, must be programmed and designed through the use of complex software and algorithms with some understanding of mission goals as well as the outcomes for the actions it performs. Moreover, the functional Human Machine Interfaces (HMI) must assist the supervisors in understanding what the system is doing, what actions it is taking, and any relevent uncertainty encountered (Finn & Scheding, 2010).

Another critical component of any AVS is its ability to effectively navigate within the operating environment. This feature, like many present in the system, relies heavily on the inputs, and resulting actions, from other components. By taking input from localization and perception components, the system processes data and is able to build a map of its environment and determine how to navigate within that environment, while detecting and avoiding obstacles that would impact mobility (Finn & Scheding, 2010). From this, the system directs controlling actions and behaviors to execute a mission.

These four core components of the AVS (mission payload, communications, human interaction, and navigation) are connected in a continuous cycle, both depending on and facilitating one another. They allow for the other functions such as system response, behavior, perception and planning. Once integrated with onboard computer processing power, software, and algorithms, the completed component cycle is what drives system autonomoy and mission/task accomplishment. The core component cycle is depicted in Figure 4.

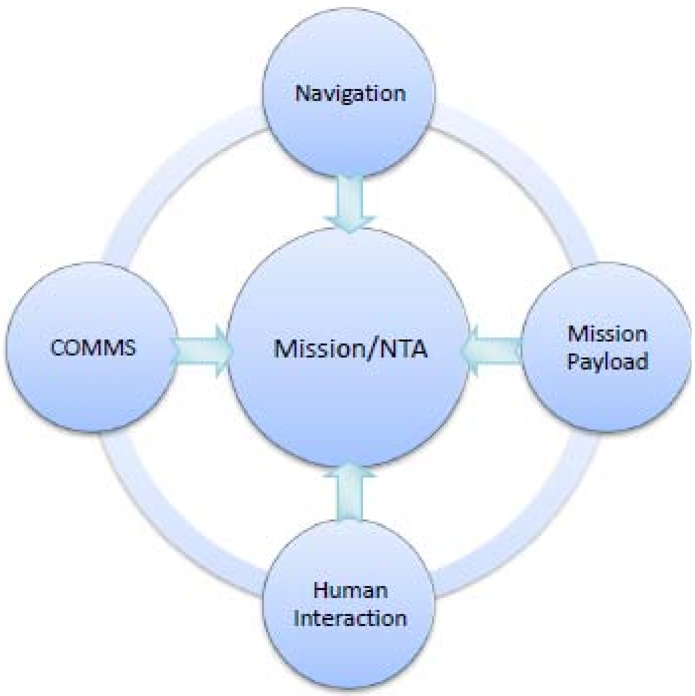

Figure 4. AVS component-mission relationship cycle

From the previously referenced functional component diagrams, sub-components and the capabilities they deliver to the system can be further itentified. It is these capabilities that also contriute to system autonomy and allow for the execution of mission tasks. The derived sub-components and capabilies are depicted in Table 1. While the list of sub-components is not exhaustive, it does cover many of the more common items in use with modern AVS. The capailities delived by these sub-components are, of course, at varoius levels of system maturity based on technology development. When taken together they represent the same necessary processing, integration, and understanding of

information required of warfighters in complex military environments. The trend toward system autonomy is also a trend toward the level of artificial intelligence required to operate at or near the level of humans. Moreover, these capabilities are critical for future AVS acting as peers and effective force multipliers.

Table 1. Component capability table

Component Capability Table		
Component	**Sub-Components**	**Capailities**
Navigation	• GPS Waypoint • Terrain Mapping • Dead Reckoning	• Mobility • Obtacle Aviodance • Path Planning
Internal Sensors	• Pressure Sensors • Velocity Sensors • Health and Usage Monitoring (HUMS)	• Localization • Self Diagnosis
External Sensors	• Intertial Measurement Unit • Magnetic Compass • GPS	• Localization
Environmental Sensors	• RADAR, LIDAR • EO/IR • Acoustic • SIGINT • Laser Rangefinder • Laser Designator • Moving Target Indicator	• Perception • Sense-making • Situational Awareness • Task Planning • Target Acquisition/Tracking/ Identification
Communications	• SATCOM • LOS (HF/UHF/VLF)	• Collaberation • Information Sharing
Computing Power	• System Software • Processing Power • Decision/Logic Algorithms	• Control • Data Integration/Fusion • Decision Making
Payloads	• Sensor Pakages • Mission Specific Components	• Task/Mission Completion

Future advances in autonomous capability can be directly linked to advances in computer processing power, which is a function of speed and memory. The computing power, which includes associated software and algorithms, are essential for all components of the overall system. Using an extrapolation of Moore’s Law, which states that computer processing speed doubles approximately every 18 months, Nick Bostrom

published a study in 1998 that equated computer processing power to that of the human brain. From this, he was able to estimate roughly when computers could achieve human equivalence. The human brain contains about 10^{11} neurons, with each neuron containing about 5000 synapses, and with signals transmitting along those synapses at about 100Hz. Estimating that each signal contains 5 bits, this equates to 10^{17} operations per second, or 10^{11} millions of instructions per second (MIPS), for human brain performance (Bostrom, 1998).

In a similar study, Moravec concluded that the human brain was capable of 10^8 MIPS, based on his analysis of human retina processing and computer vision techniques. As far as memory capacity, the ratio of memory to speed has remained relatively constant over the course of computing history, giving that 1 byte/ops. Therefore, the human brain's memory capacity is approximately 10^8 Mbytes (Moravec, 1998). The relationship between processor speed and memory is presented in Figure 5.

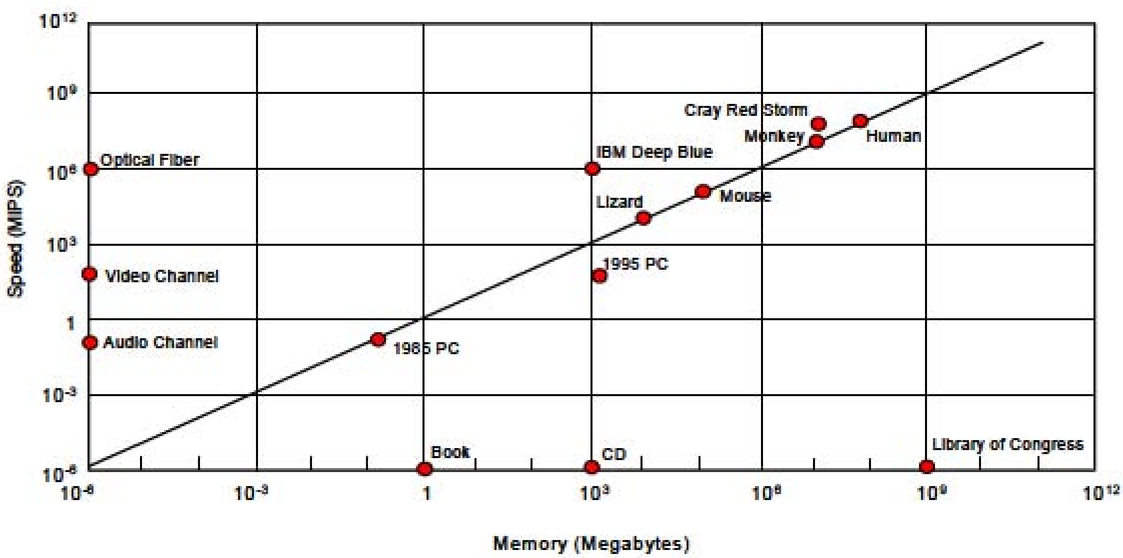

Figure 5. Relationship of processor speed and memory (From OSD, 2007)

Both studies took into account processing speeds available at that time, as well as physical limitations of micro-processor technology and the cost trends for manufacturing high performance processors. Assuming that the physical limitaions could be overcome

and the costs associated with manufacture decrease over time, estimates based off Moore's Law put realistic, affordable computer processing power equal to that of humans somewhere in the 2020–2025 timeframe (Bostrom, 1998; Moravec, 1998).

B. FUTURE AUTONOMOUS CAPABILITY

In order to derive the possible operational, organizational, and C2 implications of future autonomous systems within the maritime domain, it is necessary to first develop a set of expected near term (within the next decade), capabilities of those systems. Based upon current applied R&D efforts, expected advances in sensor and computing technology as well as ever-increasing budgetary investment and organizational commitment, it can be reasonably assumed that autonomous systems will become considerably more capable and reliable in a few specific areas. This increase in capability and reliability will allow these systems to conduct an expanded set of operational naval missions in support of the warfighter.

The DoD envisions a force of future UVS that support and enhance the ability of the warfighter to conduct a wide range of missions within the battlespace more effectively and with less risk (OSD, 2009). Autonomy is viewed as a key capability of these systems to deliver minimized manning and bandwidth requirements while "extending the tactical range of operations beyond the LOS" (OSD, 2007). Cooperative Autonomoy also allows for these systems to operate in an integrated, collaborative manner with other UVS as well as manned assets for mission accomplishment in dynamic environments, and across multiple Joint Capability Areas (JCA). Developing the associated technologies that will enable complementary collaberation is of paramount importance to the organization, and is the focus of several current R&D efforts.

It is the goal of the DoD to invest in future technologies and system solutions that can be applied across multiple operating domains and JCAs in keeping with the JCIDS process. Within the realm of unmanned and autonomous systems, there are certain key technology areas that are common to the advancing of capability in all three operating domains, while other technology investments and development will need to be domain specific. Advances in autonomous related technology will be an incremental process,

requiring sustained commitment from all parties involved in the R&D efforts. An analysis of DoD strategy documents and master plans allows for assessment and estimation of when these key technology solutions are expected to be available to the warfighter in the form of system capabilities. Figure 6 depicts a few major technology areas common to all operating domains, where targeted R&D efforts are underway.

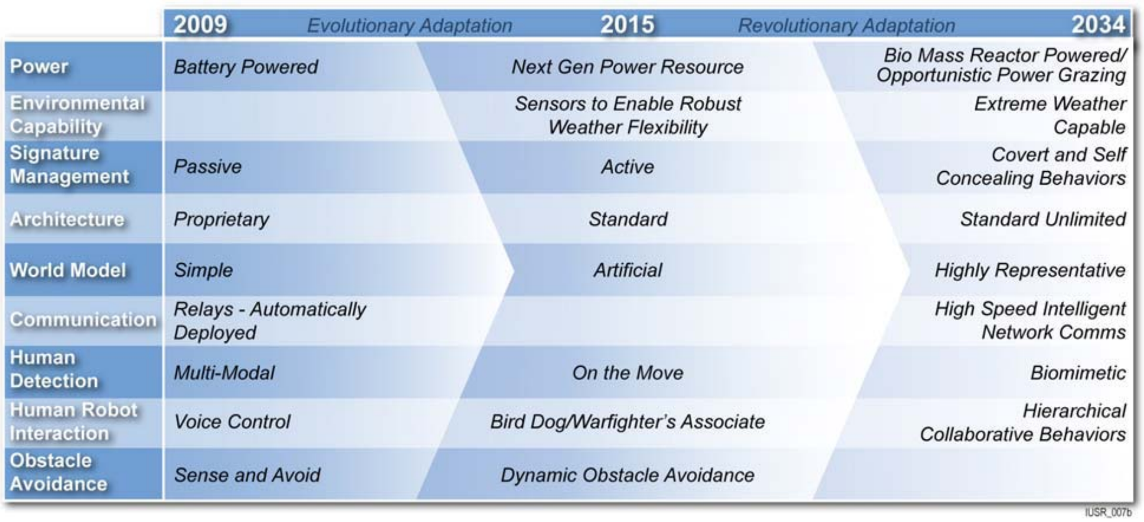

Figure 6. Technology enablers common to all domains (From OSD, 2009)

Technologies such as human robot interaction, human detection, and advanced autonomous navigation and obstacle avoidance are identified as critical for success in future systems employment, regardless of operating domain. For example, developing technology solutions that enable the system to act as more of a partner and collaborator with the warfighter are in keeping with the Department's vision for future autonomous systems. Much of this capability depends on further development and integration of onboard sensor systems that contribute to overall awareness.

Likewise, the ability of the system to detect and classify humans from other contacts within the environment will contribute greatly to system awareness and task completion. Supporting emerging technologies include human skin detection, LIDAR, microwave, and visual sensors that are currently being developed by multiple agencies within DoD and industry. These technologies and the capability they bring are expected to be available to the warfighter by the end of this decade (OSD, 2009).

1. Maritime Domain Specific Future Capabilities

As part of the SPAWAR SSC San Diego USV project, technologies enabling dynamic obstacle avoidance and path planning are being tested. The obstacle avoidance capability has two components operating simultaneously: a reactive, or near field, and a deliberative, or far field (Nguyen et al., 2009). The deliberative component continuously modifies the existing route of the vehicle to plan around both fixed and mobile obstacles, whereas the reactive piece avoids obstacles in close proximity to the vehicle. This obstacle avoidance capability is accomplished through the integration of sensors including marine RADAR, Automatic Identification System (AIS), monocular vision, and LIDAR. Nautical charts are also used and programming takes into account the maritime rules of the road, though this is still somewhat limited. As the obstacle avoidance capability continues to mature, reliable autonomous navigation within the complex maritime environment is likely within reach.

Additionally, the Autonomous Payload Deployment System (APDS) project aims to enable a vehicle platform to autonomously deliver a variety of mission payloads, including stand-alone sensors, IR illuminators, communications relays, or ammunition within the battlespace. An onboard deployment module can deliver a payload based on pre-programmed response to environmental conditions or by remote control (Nguyen et al., 2009). Experimentation and testing is currently limited to UGVs in use at SPAWAR SSC Pacific for EOD missions; however, potential application in the surface and underwater domains is likely as the associated technology continues to advance. The capability of a vehicle to autonomously detect, react, and respond to its environment by delivering mission- or task-specific payloads crosses the threshold between systems that are passive and those that become more interactive in their operational employment.

In the area of human robot interaction, the Program Executive Office for Littoral and Mine Warfare (PEO LMW) is developing the Unmanned Systems Common Control (USCC) software integration architecture for use with the Littoral Combat Ship (LCS) and its initial mission package modules. Those Phase 0 mission packages include Anti-Submarine Warfare (ASW), Mine Countermeasures (MCM), and Surface Warfare

(SUW). The USCC is intended to provide a “strategy and open business approach to ensuring that control of unmanned maritime systems is common across vehicles and across missions” (PEO LMW, 2009). The software system resides on the LCS Mission Package Computing Environment host hardware, and provides standard interfaces and common applications for unmanned vehicle control across mission packages. In addition to integration with mission packages and individual unmanned vehicles, USCC also provides interfaces to the LCS specific Combat Management System (PEO LMW, 2009). A high-level veiw of the USCC and its relationship to other ships’ systems is shown in Figure 7. The USCC functional components include Navigation Control, Mission Planning, Recorder Management, Common Mission Control, and Unmanned Vehicle Interface. Together, these componenets contribute to collaberation, coordination, supervison and control of assets in the execution of a mission.

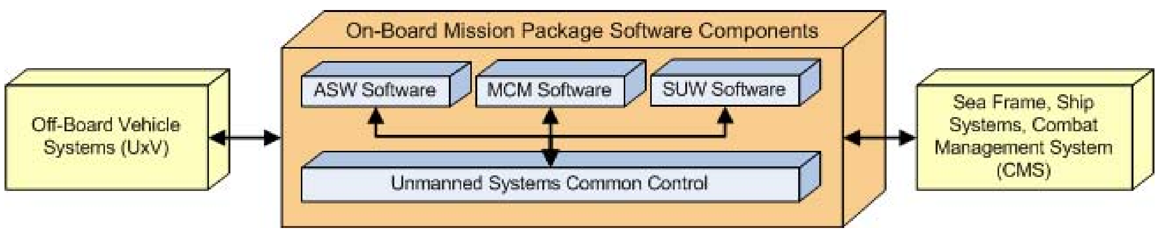

Figure 7. Top-level view of USCC in LCS context (From PEO LMW, 2009)

While currently limited in development and testing to the LCS and its current mission packages, the USCC architecture has envisioned future applications for emerging unmanned and autonomous systems as well as other host platforms. Long-term standardization and commonality of hardware and software components will contribute to future interoperability across missions and operating domains (PEO LMW, 2009). USCC represents a concentrated effort by the Navy to further standardize and integrate the various vehicle systems, regardless of mission, to existing manned assets. This focus on delivering advanced and robust human machine interaction capability to the warfighter will allow the service to better leverage the emerging unmanned and autonomous systems entering the fleet.

C. NAVAL TACTICAL TASK LIST (NTTL)

The NTTL is a sub-component of the Universal Naval Task List (UNTL) and is meant to provide a comprehensive hierarchical listing of the mission related tasks that can be expected to be performed by naval forces (DON, 2008). The NTTL also identifies variables within an operating environment that may affect performance of a given task, as well as assigns generic measures of effectiveness (MOE) that a commander can then tailor to establish a detailed standard baseline of performance for his or her unit. As stated by instruction, the NTTL only defines what operational tasks are expected to be performed, and not who will perform them or how (DON, 2008). These details are left to service specific doctrine, CONOPS, and Tactics, Techniques, and Procedures (TTP).

Ultimately, the NTTL uses a common language and provides a framework for further development of Navy Mission Essential Task Lists (NMETLs) by a commander. NMETLs provide a “command specific listing of critical tasks, conditions, and standards required to perform a command’s mission” (Brown, 2007). NMETLs are primarily used for unit training and evaluation as well readienss reporting as a part of the larger Navy Warfare Training System. A commander can and will select many tasks from the NTTL that pertain to the accomplishment of his or her assigned mission for specific tailoring into NMETLs. For the purpose of this analysis, selected maritime operational threads will be taken from, and limited to, the NTTL based on the likely impact of future autonomous capabilities in the near term.

1. Mine Countermeasure Operations

Given the previously identified expected near-term advances in AVS technology and capability, the Mine Warfare (MIW) community stands to be affected greatly by the increased introduction of autonomous systems over the next 10 years. To be sure, current field experimentation and testing have shown success in the use of tele-operated UUVs for detection and identification of mine-like contacts (MILC). Fleet MCM surface units are aging and the trend would seem to imply that the Navy has acknowledged a major shift in the structuring of the MIW field. The requirements for MCM operations revolve around the need to establish and maintain safe fleet operating areas and transit routes

(Q-routes) for Carrier Strike Groups (CSGs) and Amphibious Readiness Groups operating both in the open ocean and in the littorals (NUWC, 2004). MCM and its component mission types focus on determining the presence or absence of mines in a given area (mine hunting) as well as neutralization of the mine threat.

The NTTL describes MCM operations under the broad task of maintaining mobility of naval forces, a subcomponent of Naval Task (NTA) 1: Deploy/Conduct Maneuver. Subordinate of maintaining mobility are the several MCM related sub-tasks, which are summarized in Table 2. The central process in MCM is the ability to reliably detect, identify, classify, mark, and then neutralize mines. This process is accomplished through the use of multiple platforms, currently both manned and unmanned, and through a variety of sensors. The critical constraints to this process are time and space; the time required to complete mine hunting and neutralization, and the total area searched and then cleared.

The MOE associated with MCM related NTAs generally exemplify the central process and constraints identified above. Ultimately, MCM is conducted to mitigate risk (probability of damage) to friendly forces/ships. This probability of damage is defined as the expected value of the probability of damage to ships/units given a certain number of mines remaining in the operations area at the completion of MCM efforts (Cramer et al., 2009). The other MOE specifically address the issues of time required to complete marking and clearing of mines, total area searched and cleared, and percent accuracy of MILC properly identified and classified.

The current version of the Fleet Unmanned Undersea System CONOPS goes into great detail about the nature of UUV development and operation in current as well as future mission roles. With regard to MCM operations, the CONOPS envisions future teams of Autonomous Underwater Vehicles (AUV) operating in concert with one another as well as with manned assets to reduce timelines required for search, identification, and classification of mines within a given area of operations (AO) (DoN, 2010). Currently, UUVs collect data pertaining to the area of interest (minefield) and then are recovered by manned assets for data analysis and interpretation. The benefit of utilizing teams of advanced AUV for MCM is that by coordinating and leveraging the information each

vehicle collects in real-time, the interpretation and analysis of the threat (presence of mines) can occur in a timelier, more reliable manner with minimal danger to humans.

Table 2. MCM-related Navy tasks

NTA	Description	Measures of Effectiveness (MOE)	
		Units	Measures
1.3.1 Perform Mine Countermeasures	To detect, identify, classify, mark, avoid, neutralize, and disable (or verify destruction of) and exploit mines using a variety of methods including air, surface, and subsurface assets.	Percent	Residual risk to friendly forces
		Hours	To complete clearing of mines
		Nautical Miles	Cleared operations area
1.3.1.1 Conduct Mine Hunting	To detect, locate, and mark mines that present a hazard to force mobility in an overt, covert, and/or clandestine manner. The employment of sensor systems (including air, surface, and subsurface assets) to locate and dispose of individual mines. Mine hunting is conducted to determine the presence or absence of mines in a given area.	Nautical Miles	Area searched
		Hours	To complete marking of mine field
		Number	Mine-like objects found
1.3.1.1.1 Reacquire Mine-like Contacts (MILC)	To reacquire a MILC using one or more of several search techniques, to include all surface, air, and underwater techniques.	Percent	Of all mine-like contacts reacquired
1.3.1.1.2 Identify Mine-like Contacts (MILC)	To identify a MILC through various observation techniques (i.e., divers' eyes-on, remotely operated vehicle (ROV) pictures, and live or recorded video) as either a mine or non-mine.	Percent	Accuracy of objects identified
		Percent	Of objects Identified

a. Cumulative Detection Probability

An applicable platform level performance metric for future teams of AUV conducting MCM is Cumulative Detection Probability (CDP), which is a function of sensor performance, time on station, and coverage factor (total search area) (Tutton, 2003). Detection is the critical first step in MCM operations and therefore the ability of an AUV to first accurately detect a MILC and also build a map of its surroundings

becomes necessary for all other aspects of the MCM mission. Presumably a team of AUV, if able to share localization and contact data in real-time, would be able to build a collaborative map of the AO. This would undoubtedly contribute to increased CDP, ensuring most, if not all, MILC are accounted for within a defined AO.

Revisiting a 2003 study provides an example analysis with appropriate definitions and equations necessary to calculate CDP. Tutton defined platform level sensor performance in terms of adjusted sweep width and sensing velocity. Adjusted sweep width takes into account the likelihood of multiple sensors mounted on the same platform, then selects the sensor with the maximum sweep width and applies a dependence factor to the remaining cumulative sum of the other sensor sweep widths (w_s). This dependence factor (α) is applied to account for the added benefits of multiple sensors on the same platform. The resulting equation, as derived by Tutton, is:

$$W_{adj} = MAX(w_s) + \alpha * \{\sum (w_s) - MAX(w_s)\} \qquad (1)$$

The assumptions associated with calculating adjusted sweep width include optimum sensor package combination for the assigned mission, and that the platform operates at optimum range for the sensors associated with it and the target type of interest (Tutton, 2003).

In order to calculate time on station, it is necessary to factor in transit speed of the platform to and from the search area, sensing velocity, and total operational time for the platform, i.e., the total amount of time the platform can remain operational while transiting and searching. Time on station is thus determined by:

$$\text{Time on Station} = T_{op} - (2 * \frac{D}{V_t}) \qquad (2)$$

(T_{op}) is the total operational time, (D) is the distance to the search area, and (V_t) is the transit speed of the platform.

The third factor in calculating CDP as defined by Tutton is the coverage factor, or total search area covered. Coverage factor is determined by assuming a fixed AO (minefield), and taking into account sensing velocity, time on station, and adjusted sweep width (Tutton). The resulting equation is:

$$\text{Coverage Factor} = \frac{v_s W_{adj} t}{A} \tag{3}$$

This coverage factor is the ratio of search area swept by the platform, where (v_s) is the sensing velocity, (t) is the time on station, and (A) is the total AO. From these calculations, CDP can be calculated for multiple platforms of the same type (p) by assuming that each individual platform is able to search an equal portion of the AO.

$$F_d(p) = 1 - e^{-\frac{vW_{adj}t}{A\frac{1}{p}}} \tag{4}$$

After a brief example that included reasonable values for the associated variables defined above, and taking into account the assumptions related to each calculation, Tutton was able to graphically depict a CDP curve showing a positive correlation between number of platforms and CDP. The CDP curve is presented in Figure 8.

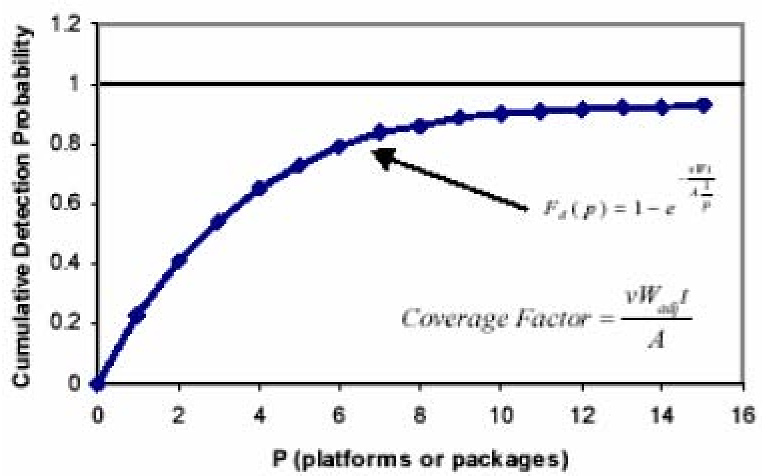

Figure 8. Cumulative Detection Probability (CDP) curve (From Tutton, 2003)

The preceding performance metric example is scalable and meant to illustrate the benefit of utilizing multiple, collaborative sensor platforms in the execution of a particular mission. Based on emerging AUV payload capabilities, as well as advances in navigation, localization and 3D mapping, the other components of the MCM process, i.e., identification, classification, and marking of MILC, are likely to become increasingly automated in the near term. This trend implies major

tactical as well as operational implications for the future of MIW and will require shifts in organizational design and thinking.

2. Maritime ISR

In its broadest sense, ISR is concerned with the synchronization and integration of sensors, assets, processing techniques, and dissemination systems to support current and future military operations (Department of Defense, 2001). It is the fusion of several intelligence and operations fucntions to form an integrated support discipline for the requirements of the warfighter. The production of intelligence is a result of the collection, processing, analysis, and dissemination of raw data into valuable information that can then be used for decision making and mission execution. The concept of ISR takes this process a step further and adds the requirement for shared understanding and battlespace awareness across multiple operating domains.

Maritime ISR requirements span all three domains of naval operations; surface, sub-surface, and air. In order to achieve shared understanding and SA, platforms and assets need to be networked and integrated to produce reliable information about the operating environment, thereby supporting the Navy's FORCEnet operational construct. A major requirement associated with maritime ISR is the need for long-dwell, persistent platforms capable of acting as communications relay nodes and sources of information for operational naval commanders. Furthermore, the information produced as a result of maritime ISR efforts needs to be fully integrated into the Maritime Operations Center (MOC) C2 architecture as well as the larger Global Information Grid (GIG) (DON, 2008).

The NTTL addresses several ISR related tasks under the umbrella of NTA 2: Develop Intelligence. The sub-tasks identified in Table 3 represent a few of the component activities necessary to develop Intelligence Preparation of the Operating Environment (IPOE); namely surveillance, reconnaissance, and collection of data associated with an AO. The data associated with an AO includes anything from geographic features to location and disposition of enemy targets as well as friendly

forces. MOE associated with these tasks are concerned with evaluating the time required to position, or re-position, assets in place and percent of all collection requirements fulfilled.

Table 3. ISR-related Navy tasks

NTA	Description	Measures of Effectiveness (MOE)	
		Units	**Measures**
2.2.1 Collect Target Information	To acquire information that supports the detection, identification, location, and operational profile of enemy targets in sufficient detail to permit attack by friendly weapons. Activities include searching for, detecting, and locating targets; and then tracking to include information such as range, bearing, altitude/depth, latitude/longitude, grid, and course and speed of the target.	Days	From receipt of tasking, information available
		Percent	Of collection requirements fulfilled by recon/surveillance assets
		Percent	Of time able to respond to collection requirements
2.2.3 Perform Tactical Reconnaissance and Surveillance	To obtain, by various detection methods, information about the activities of an enemy or potential enemy or tactical area of operations. This task uses surveillance to systematically observe the area of operations by visual, electronic, photographic, or other means. This includes development and execution of search plans.	Days	From receipt of tasking, unit reconnaissance and surveillance assets in place
		Percent	Of collection requirements fulfilled by reconnaissance and surveillance assets
		Percent	Of time able to respond to collection requirements
2.2.3.1 Search Assigned Areas	To conduct a search/localization plan utilizing ordered search modes/arcs	Hours	From receipt of tasking until search force is in place
		Hours	To respond to emergent tasking(s)
		Percent	Of time able to respond to collection requirements

It is once again appropriate to recognize reliable detection as an indispensable enabling performance factor of any asset employed for ISR purposes. Without a high CDP, the follow-on functions identification, tracking, and overall battlespace awareness cannot be carried out. Achieving as high a CDP as possible requires not only versatile sensor equipment, but also optimum tasking and allocation of platforms within an AO so

that reduction in false-positive detection rate is possible. The environment in which maritime ISR assets operate (primarily air and surface) however, is significantly more cluttered than that of MCM platforms, so the problem of detection and differentiation is made exceedingly more complicated. Within the realm of ISR, it is of course not simply the detection and identification of MILC, but rather a whole range of possible small/large objects, contacts, targets, terrain features, weather affects, and indeed, humans. The complicated, and potentially hostile, operating environment with its numerous data collection requirements suggests a need for highly intelligent AVS.

The utilization and incorporation of UVS, particularly within the air domain, for ISR-related tasking is evolving to the point of relative maturity, especially as the capabilities for increased persistence and rudimentary perception continue to improve. However, the data collected from these systems during the course of their tasking must still be transmitted, and then analyzed and interpreted by human supervisors/operators before any useful information about the AO can be produced. The time required to turn raw data into valuable information varies, depending on myriad intermediate technology and human cognitive processes. The desire to achieve automated data analysis and interpretation is a stated goal of future DoD AVSs and is the subject of several current R&D projects. Providing reliable and trusted information to the warfighter in as short a time as possible is in fact one of the component functions of intelligence operations. These AVSs will need to be capable of fusing data inputs from multiple onboard, as well as networked, sensors providing a variety of data pertaining to the AO.

a. Situational Awareness

Developing and maintaining good SA is arguably one of the most critical human cognitive factors associated with the successful execution of military operations, from the tactical through the strategic level. While many definitions of the term exist, they all tend to revolve around a central process; the perception of the elements of the environment, comprehension of their meaning, and projection of that understanding into the near future in order to take action (Endsley, 1995). Each component of this process equates to a corresponding level of SA according to Endsley. Naturally, as the

complexity associated with the environment increases, so too does the cognitive workload required to achieve and maintain SA in order to make informed decisions (Endsley, 1995).

When developing SA, humans rely on inputs from all five of the senses to perceive environmental conditions that relate to the completion of mission goals and tasks. We have the ability to distinguish relevant from non-relevant and can adjust our sensory attention accordingly based on changes in our surroundings (Adams, 2007). Next, we achieve comprehension by integrating our perception of the environment as applied to our understanding of mission goals and experience from memory. Finally, from our perception and comprehension of the mission environment, we are able to predict what will occur in the near-term, which is typically a highly demanding cognitive activity and can be limited depending on workload, stress, and metal capacity (Adams, 2007).

With regard to AVSs, current platforms are beginning to exhibit basic level environmental perception capability, from the integration of onboard sensors and computer processing power. As previously discussed in this chapter, that perception capability is both internal and external, e.g., navigation and localization related and mission task related. Advances in onboard sensor and computing technology will presumably allow for better contact and target detection, tracking, and identification, especially when integrated with other platforms and/or humans. The challenges for achieving machine SA are in the area of comprehension and prediction. Logic algorithms result in most systems being highly reactive to their environment, without a real comprehension of their overall mission goals. R&D in the areas of artificial intelligence, machine learning, and 3D world modeling applying highly complex mathematical models are addressing the challenges associated with simulating complex human cognition in future AVSs.

A discussion of SA leads to an expansion of the concept of levels of autonomy present in the system. Numerous definitions and interpretations of autonomy levels exist, but generally system autonomy characteristics range from full human control of the vehicle (no autonomy) to complete removal of the human from all functions of the system (full autonomy). The common denominator is the degree of human interaction

with the system in the course of its mission. Adams correlated levels of autonomy to levels of both system and human SA. Direct human control of the system, i.e., most current UVS, would equate to little, if any, machine SA, while fully autonomous systems would reduce considerably the level of human SA (Adams, 2007). Figure 9 provides a basic representation of the relationship between levels of system autonomy and levels of SA, for both the machine and the human.

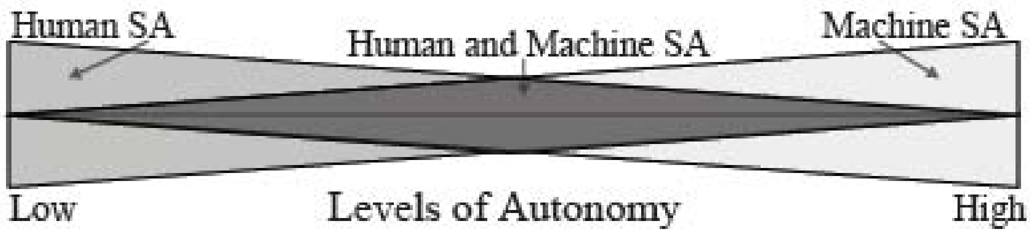

Figure 9. An allocation of human and UMS SA across the levels of autonomy (From Adams, 2007)

The preceding discussion of SA is meant to illustrate a necessary attribute that machines will need to possess when conducting maritime ISR. There are of course other attributes that will be critical such as threat recognition and avoidance, robust communications capability, and system signature management to name a few. However given the dynamic, data intensive nature of this mission set, future platforms will need to develop some level of overall SA in order to effectively act as reliable collaborators to their human counterparts and/or supervisors.

Reduction in the cognitive workload required by humans when conducting data analysis and interpretation requires these systems to be capable of advanced, adaptive behaviors based on environmental conditions and mission goals. These mission goals translate to comprehension of intelligence collection requirements as well as the ability to process raw data into useful information. An obvious benefit of incorporating highly intelligent and persistent AVSs, with the capability for SA and simulated human cognition, into maritime ISR mission sets is the dramatic reduction in the time requirements associated with IPOE.

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IV. ORGANIZATIONAL CHANGE

A. REVOLUTION IN MILITARY AFFAIRS (RMA)

This thesis has documented examples of current UVS and AVS employment, explored expected future technology and capabilities, and has provided analysis of possible impact to maritime warfare areas. The continued growth in technology and capability of these systems, coupled with improved performance within the battlespace, suggest an impending RMA. As the human element is removed more and more from the tasks, processes, and decisions associated with military operations, the organization that those systems support will undoubtedly be required to undergo a transformation in order to best align its changing components.

Throughout its history, technology innovation has contributed to several periods of transformation within the U.S. Military. This is argued to be especially true of the twentieth century, where the period between major military innovations decreased as a result of two world wars, a political and ideological Cold War, and vast changes in organizational commitment to R&D as well as performance measurement (Murray & Millet, 1996). Innovation is also driven by the desire to remain "a step ahead" of an adversary or potential adversary, as the organization recognizes the likelihood of equal employment of capability within the battlespace.

The introduction of naval air power, coupled with the adoption of the aircraft carrier, provides an appropriate historical example to illustrate an RMA experienced by the U.S. Navy in the period between the two world wars, culminating with their full integration and relative maturity in the Pacific theater of World War II. Advances in aircraft design and performance capability during the 1920s and 1930s, as well as lessons learned from limited employment during the First World War, led to a transformation in the structure and operation of the U.S. Navy's battle fleets. To be sure, this transformation did not occur overnight. It was resisted by many naval leaders of the time, and has been argued to be a function of necessity during the interwar period, given the next perceived strategic threat (Japan) and the geographic circumstances of the vast

Pacific where that threat would be met. This required a naval fleet capable of providing its own organic air cover far from land bases (Murray & Millet, 1996).

This level of strategic thinking by leadership at the time highlighted the realization that naval air power could be employed for direct attack against enemy fleets and merchant targets, as well as for close air support for amphibious operations. Employment of maritime air power in such a manner would require further maturity of training, maintenance, and support structures already beginning to emerge within the organization. The immediate aftermath of Pearl Harbor also no doubt contributed to the necessity of naval air power, as well as silenced any remaining critics as to the effectiveness of carrier-based aircraft. Thus, by the time the U.S. Navy was fighting Japan for sea control in the Pacific, the fleet was structured around carrier task forces able to project power via their embarked air wings. No longer was the battleship the centerpiece of warfare at sea, as opposing fleets would often fight one another without ever coming into direct contact.

This example illustrates how the Navy was forced to integrate a new technology innovation into its existing organizational structure, ultimately causing a strategic shift in how maritime operations were conducted in order to best leverage the capability presented. The shift is of course fully realized today, in the form of a CSG centric fleet able to project power globally in support of the nation’s strategic objectives.

B. ORGANIZATIONAL PERFORMANCE

The type of large-scale change that usually results from an RMA cannot occur without first understanding the organization’s components, their relationships, and how they perform as a whole in the accomplishment of stated goals and missions. Gaining an appreciation of these complex aspects of organizational design, and how they impact one another, allows leadership to implement changes that best contribute to improved performance over time. Research in the field of organizational and open systems theory has shown that any complex organization can be thought of as a system of inter-connected social and technological factors working together for some common output. In general, this is accomplished by taking various input factors from the system’s

environment, transforming them through some process or combination of processes, and then producing an output (Mercer Delta LLC, 1998). This process, complete with feedback provided by output to affect new input, is depicted in Figure 10.

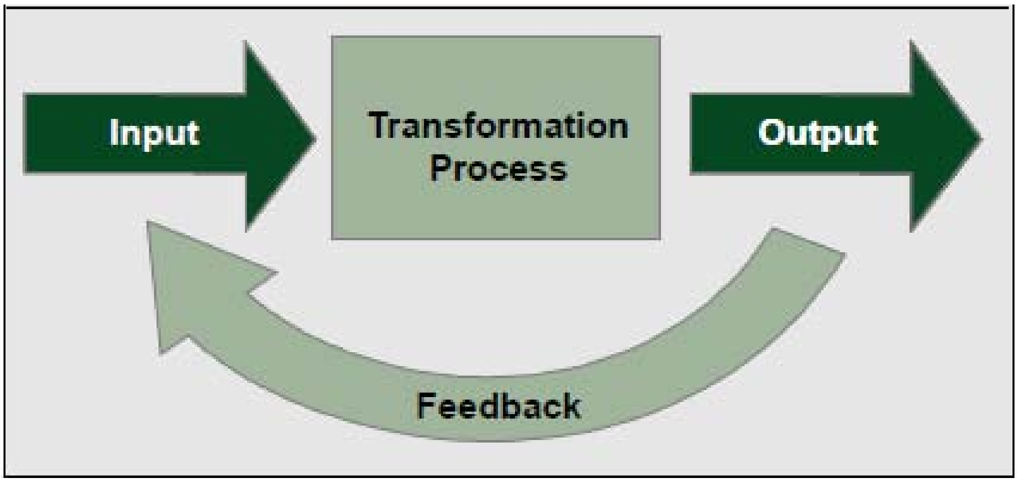

Figure 10. The basic systems model (From Mercer Delta LLC, 1998)

This model provides a basic representation for how any system, or for that matter organization, operates. To understand an organization's performance however requires something more.

1. The Congruence Model

By looking at all of an organization's components in terms of an inter-related system, the Mercer Delta Congruence Model is used to asses performance based on how the components "fit" or align together in the accomplishment of goals. Building upon the basic systems model, the Congruence Model identifies organizational inputs, components of the transformation process, and outputs in terms of what is produced and the performance at various levels of the organization. The model can also be used to help leadership gage the impact of minor or large-scale changes and how those changes will affect the concept of component congruence. As stated, the model "provides a very general roadmap or starting point on the path to fundamental organizational change" (Mercer Delta LLC, 1998). The Congruence Model is depicted in Figure 11.

Every organization is affected by factors relating to input, which the model defines as environment, resources, and history of the organization. Examples include other competing organizations, policies, new technologies, economic conditions, information, past strategic decisions, and organizational values. These input factors are considered “givens” by the model and exist largely external to the organization itself but define the demands, constraints, an opportunities present (Mercer Delta LLC, 1998).

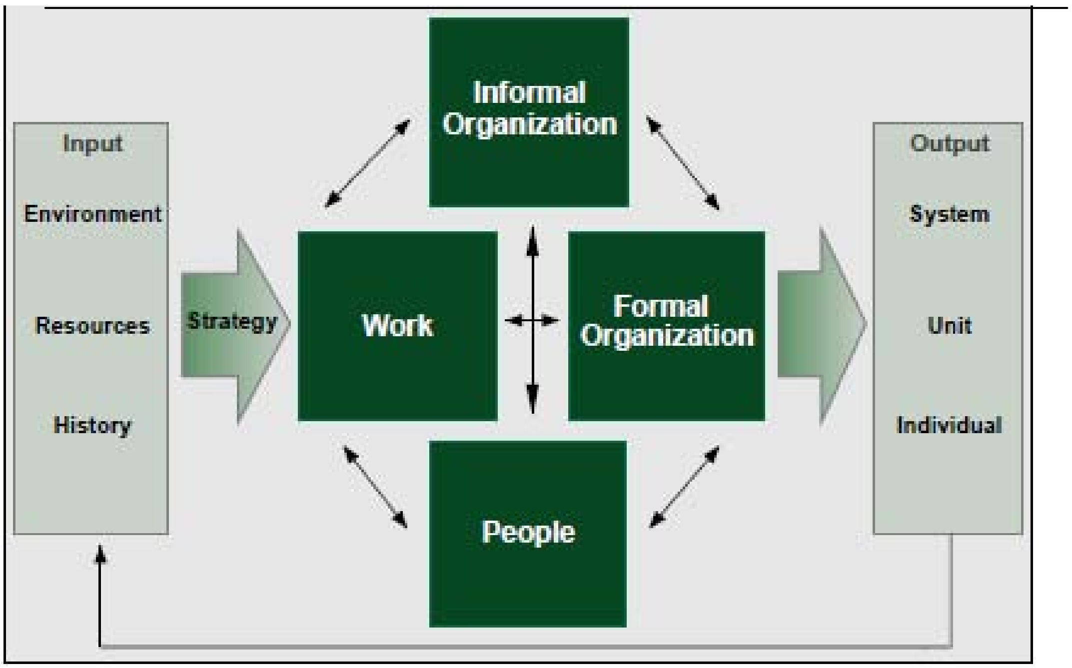

Figure 11. Congruence Model (From Mercer Delta LLC, 1998)

Central to the Congruence Model is the organizational transformational process, which is composed of the four key components of the organization; the work, the people who perform the work, the formal organization, and the informal organization. The work is the actual activities, tasks, and processes performed by the organization that are necessary to produce output and the people are responsible for execution of those processes. With regard to people, training, experience, and perception of their role in the overall organization must also be factored in. The formal organization refers to the “formal structures, processes and systems that enable individuals to perform tasks” (Mercer Delta LLC, 1998). These are usually well established and allow for further sub-

organization and explicit guidance based on skills and capabilities to achieve strategic objectives. Finally, the informal organization component encompasses emerging processes, unwritten rules and practices, as well as other relationship dynamics that also contribute to individual behavior in the performance of their work. The informal organization can also be thought of as new and innovative business processes that can either compliment or conflict with more established, formal structures.

Once again, by identifying and recognizing what the components of the organization are, as well as how they impact one another, a continual assessment of component congruence as related to organizational performance can occur. Likewise, managers can predict the likely impacts on the organization as a whole from implementation of change to one or more of its components.

2. Impact of Machine Autonomy

Emerging AVSs represent a significant disruption to the environment with which the U.S. Navy operates. As applied to the congruence model, these systems and the capabilities they are bringing to the battlespace—as discussed in this thesis—signify an external technological innovation that the organization will have to incorporate. When taken together with increasing overall organizational commitment to these systems in the form of funding and R&D, the introduction of advanced AVS as an external variable demands that the Navy adapt and fully integrate them into its organizational structures. Moreover, the realization that the U.S. is not the sole nation interested in this technology area requires us to remain ahead of our peers and competitors.

Changes to the external environment can cause a ripple effect throughout the organization. This invariably leads to strategic level thinking and guidance about how the environment has changed or is changing, and how the organization will adapt to remain competitive. As this thesis has stated, the introduction of machine autonomy has produced organizational and warfare-area specific guidance and strategy for limited employment. The Navy is committed to the idea of fully networked, collaborative AVS that compliment and support traditional forces in the execution of their assigned missions. This goal can be thought of as the desired output for these systems, and can be

scaled across tactical or operational levels, and across multiple warfare areas. It is important to remember, however, that we are at the very beginning of what is realistically possible with these systems, and that our strategy will continue to evolve with time and experience. Recognizing what is possible now will allow for more detailed planning and guidance for the future.

Possible problem areas for the organization as a result of this environmental change are in the areas of overall performance and potential for missed opportunity when attempting to re-align the organization. For example, without well-designed and beneficial HMI in place, assessment of mission objectives and task completion will be made more difficult and performance is likely to suffer. No matter what the degree of automation, a complementary relationship between the machine and the human must be ensured. Alternatively, a lack in understanding of capability, or a marginalizing of its worth, leading to organizational reluctance has the potential to degrade the effectiveness of AVS when employed. This problem would likely stem from a lack of experience and trust in the technology available.

With regard to the Navy organization itself, all four core components (work, people, formal and informal organizations) can be analyzed based on congruence as a result of future AVS employment. The work performed encompasses the operational missions, NTAs, and core competencies that are expected of the organization as they support overall national and service strategies. They represent the reason that the Navy exists in the first place and the trend toward increasing machine automation of these activities will result in paradigm shifts across the organization. The introduction of future AVS as applied to the congruence model is depicted in Figure 12.

Naval personnel, defense contractors, and academia partners directly execute, or support the execution of, our work as an organization. Personnel will, it seems, require new and dynamic skill sets, training methods, and research and acquisition objectives that can best take advantage of the new technologies afforded to them in the form of AVS capable of conducting tasks traditionally performed by humans.

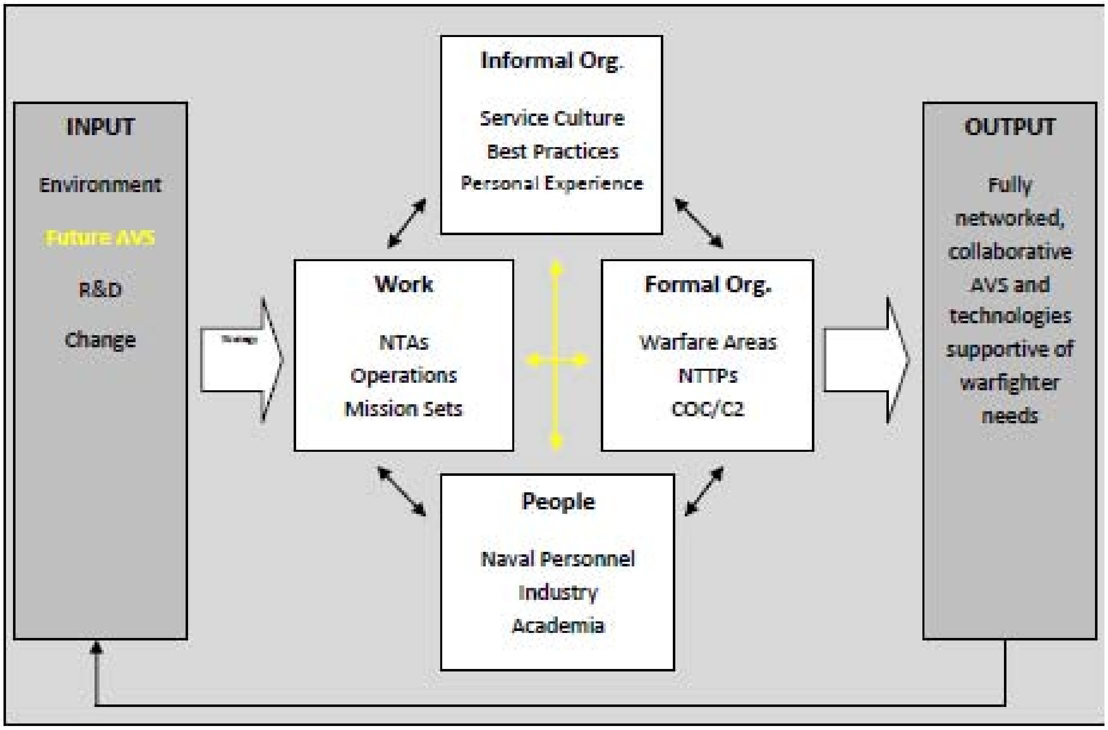

Figure 12. Congruence Model as applied to future AVS (After Mercer Delta LLC, 1998)

The formal organization consists of how we are arranged by warfare areas and supporting organization structures complete with chains of command and C2 architectures. Also present are the myriad tactical, operational, and administrative doctrine for the conduct of assigned missions. This aspect of the organization is large, complex, and bureaucratic in nature and will therefore be the most difficult to incorporate change. From type commanders, system commands, and training commands to CSGs and individual units and aircraft, the formal organization is vast and provides the framework within which our people and assets conduct assigned work. The informal organization also exists in the form of overall service culture and the values, beliefs, and emerging processes they facilitate. Lessons learned, best practices, and personal experiences also significantly shape how our people and processes are coordinated for achievement of goals.

In terms of component congruence, there is the potential for disconnect between the core components of the organization as they stand now, and the near-term introduction of intelligent AVS. Strategic guidance and R&D efforts aside, the formal organization may

not be ready for the kind of AVS employment that will be possible in the near future. Our command structures, especially at the operational level, are not well suited for mission relevant decisions and actions occurring at the speed of machine automation. The formal organization is of course made up of the people, who likewise may have problems maintaining situational awareness with their autonomous "assets" in carrying out their assigned work. It is for these reasons that the organization must attempt to shape or control the magnitude of the environmental impact from AVS. This is accomplished by the personnel and formal organizational components responsible for R&D and acquisition. They must continue to be provided with clear strategic guidance for what the organization as a whole wants in terms of performance output regarding AVS.

Likewise, there must be seamless understanding of what is scientifically possible and what is operationally effective. If ungoverned in this manner, technology development could quickly advance past the point of maximum effectiveness for the overall organization. An example would be a compounding of a problem our personnel face today; data overload from sensor assets. If data analysis and processing within the battlespace are to be made more automated in the near future, how will our personnel keep up with the vast amounts of information produced and the decisions made by AVS as a result? Posed differently, if the technology and personnel are not aligned appropriately, performance will undoubtedly suffer. Formal processes like JCIDS and DOTMLPF analysis are meant better align the R&D and acquisition communities to the personnel and missions assigned. This is even more critical now as the nature of military operations appears to be changing dramatically via increased forms of automation and autonomy, which translates to increasing levels of machine authority to conduct military operations.

The difficulties associated with integration of AVS into Naval forces and organizational structures are complex and extend well beyond the preceding analysis. However, the congruence model provides a necessary framework for understanding what makes the organization operate and how. Considering the near future, we pose three questions that guide and motivate our thinking. What if the organization can effectively re-align to leverage the enormous capability potential that will become available to it? What if AVS were true force multipliers contributing to superior operational

performance? In short, what if the desired organizational output, understood to mean collaborative human-machine warfighting capability, became reality?

C. OPERATIONAL VIGNETTE

The following example vignette is meant to help illustrate the type of collaborative behavior and performance capability that can be expected of future AVS in an operational setting. While brief, the example highlights how both manned and unmanned platforms, when integrated, can contribute to improved mission performance.

The year is 2020 and the problem of maritime piracy remains a dangerous reality for the commercial shipping industry in the waters off the Horn of Africa and in the Gulf of Aden. Coalition naval forces are committed to ensuring freedom of navigation and commerce on the high seas and possess a wealth of technology and experience in the conduct of anti-piracy operations. Information regarding a very recent coordinated pirate attack on a commercial bulk carrier transiting the Gulf of Aden is relayed to the theater MOC at Naval Forces Central Command (NAVCENT) headquarters in Manama, Bahrain. While unsuccessful in their attempt to capture the vessel, the pirates inflicted moderate damage to the ship before making their escape.

The MOC directs Commander, Coalition Task Force (CTF) 151 with locating and intercepting the pirates using any and all assets available. CTF 151 has at its disposal four surface combatants in the vicinity of the attack and two advanced airborne AVS capable of persistent ISR. Within hours of tasking, search and localization plans are formulated and executed based off appropriate time/speed/distance calculations and on estimation of the pirates last known heading. Data and information collected from each asset regarding the battlespace is networked resulting in an integrated and shared Common Operational Picture (COP) of the AO.

Arriving on station soonest, and with an understanding the related mission parameters and objectives, the AVS assets are able to perform contact identification and classification while executing their assigned search patterns. Analyzed information regarding their surroundings is relayed into the network and the vehicles, working in conjunction with one another, begin building their own world models of the AO, to

include location and disposition of friendly assets assigned to the mission. The surface combatants, with embarked rotary-wing ISR capability, are able to monitor the progress of the search in real-time through common HMI software inherent to the network and present on all platforms, including the MOC ashore. As the surface combatants begin to arrive on station, shared SA of the environment is built via the collaboration of information already obtained, the understanding of mission goals, and the projection

Approximately seven hours into the search, one of the AVS detects a potential contact of interest on the edge of its assigned search area, and immediately vectors itself closer to obtain required sensor data for positive classification. The information collected regarding the contact and the decision made by the vehicle to investigate further are fed into the network instantaneously. All other assets continue their assigned search patterns. Shortly thereafter, positive classification is made on the contact of interest by the AVS to include number of human occupants and presence of weapons onboard. This information is immediately confirmed by all manned assets within the AO to include the MOC. Based on pre-programmed knowledge of friendly platform performance capabilities and limitations, and calculations of distance, the vehicle recommends, via the network, vectoring of a manned surface combatant and helicopter asset from an adjacent search area. This recommendation is evaluated and accepted by both the manned asset in question and by the CTF and MOC commanders exercising C2 for the operation. The AVS remains in close contact with the suspect vessel until the vectored surface combatant arrives and conducts a boarding operation. Once this occurs the vehicle, with an understanding that this particular mission goal is complete, resumes its original search pattern.

Meanwhile, the remaining mission participants, operating under the knowledge of three pirate vessels involved in the original attack, refine the boundaries of the AO based on all available information and redistribute accordingly to increase the probability of intercept. At just over twelve hours into the mission, one of the surface combatants comes into contact with two pirate vessels traveling together and launches a boarding operation of its own. With all suspected pirates in custody, both AVS return to their bases, and the surface combatants resume their original duties.

V. IMPLICATIONS AND RECOMMENDATIONS

A. IMPLICATIONS

The observations and analysis presented in this thesis are meant to provide a framework for possible implications to maritime operations and organizational structure, as well as how certain aspects of C2 are impacted. The automation of military related operations will result in paradigm shifts for how we understand and conduct warfare. The preceding research has attempted to bracket what the operating environment might look like within the realm of what is realistically possible in the near-term. By doing this, major themes and characteristics related to the AVS were identified so that implications could be drawn about what they mean for the future of military operations.

The speed and tempo of operations will likely increase dramatically in the coming decade. As autonomous systems capability continues to be employed in support of maritime missions and NTAs, the timeliness and availability of information will be enhanced greatly, ultimately contributing to increased speed of action within the battlespace. This is the reason that so many of our business processes are automated today, because doing so has proven to contribute to increased organizational efficiency. Now we stand on the forefront of automating our work as an organization, which is exceedingly more difficult to measure in terms of performance, and implies the necessity for fundamental organizational change.

The speed and tempo of operations can be governed by the degree of decision authority granted to future AVSs. Invariably, as the technology and capability improves, the ability to make decisions and take action based on achieved perception and understanding will increase. This implies a merging, or compression, of the decision space between human and machine and naturally begs the question of how much of that space, or authority we relinquish. Similar to, or rather in conjunction with, machine versus human SA, there is a point at which the decision-making capability of both must be mutually beneficial. What is needed is an acceptable level of decision making authority granted to the system proportionate to mission goals, technical capability, and

demonstrated performance. Ultimately, the degree of decision making authority relinquished amounts to the degree of organizational acceptance (trust) in the system and the perceived impact on decision superiority within the battlespace.

The Navy's individual warfare area components will require clear definitions of the level of autonomy desired for future systems that it chooses to procure and field. Requirements and suitability for autonomy will differ from the MIW community to that of the Surface or Aviation communities for example due to the obvious differences in mission and the various processes used to accomplish that mission. This implies the need for an even closer, more cooperative relationship between the various system commands, its partners in industry and academia and across the entire defense acquisition organization. Likewise, it is critical that organizational guidance and CONOPS keep pace with emerging technology in the field of machine automation. A failure to accomplish this would result in poor organizational "fit" and degraded performance. Knowing how we expect the introduction of autonomy, to the extent realistically feasible, to benefit our processes, tasks, and structures is a first step toward realizing its potential.

As this research previously stated in Chapter III, full machine automation has the potential to negatively impact human SA and thus would be detrimental to mission accomplishment in any context. There are certain military operations that probably would not, and should not, ever become fully automated in nature. Warfare is an activity innate to humans, and though we use technology to gain advantage over adversaries, technology itself cannot determine the conduct or outcome of war (Potts, 2002).

The concept of "command" in the near term will become further decentralized and distributed as a result of the emerging technology discussed in this thesis. There is the potential for a blurring of the lines between operational and tactical command in the conduct of operations as a result of fully networked, collaborative AVS employment. For example, there can be no single person maintaining visibility of the information gathered and decisions made in the type of fast paced, high tempo operations that future technology will facilitate. This is acknowledged in current operating constructs such as FORCEnet and Network Centric Operations that suggest that the visibility is shared across all levels of the organization and warfighting environment simultaneously. How

does machine automation of complex military tasks impact these constructs? What if that visibility, and the SA that results from it, are achieved faster than can be beneficially shared? Put another way, what if the decisions resulting in action taken within the battlespace have already happened by the time humans realize something needs to be done? These questions are meant to emphasize the critical need for achieving proper organizational congruence as realized through clear definition of roles and desired outputs for these systems.

Likewise the term “control” will continue to evolve in meaning. No longer will the exercise direct control over assigned forces be practicable. Even the nature of today’s dynamic warfighting environments is eroding at that obsolete definition. With the speed and availability of networked information for multiple independent actors (both manned and autonomous) operating together within the battlespace of the near future, the concept of control must be approached differently. Applying Alberts and Hayes’ concept of “establishing, to the extent possible, the initial conditions that will result in the desired behavior” appears relevant. With regard to emerging AVS, this concept should be taken to mean the proper alignment of the organization’s technological and social components for the purpose of leveraging capability. On a more tactical level, this means the arrangement and allocation of forces and assets within the battlespace and the communication of clear goals and understanding of commander’s intent.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

Future R&D will of course continue in the technology areas that facilitate machine autonomy. Advances in sensor integration, computing power, threat recognition and avoidance will result in systems that are adaptive and agile. When it comes to innovation the technical side, while certainly challenging, is only half of the overall issue. The magnitude of disruption to the organization as a result of technology represents the other half and still requires further analysis. Technology traditionally evolves rapidly while organizations tend to be much slower and more resistant to change.

A great deal of time and resources are expended by the Navy, rightfully so, in the areas of training and performance evaluation. Whole sub-components of the organization

are dedicated to these activities as they provide the building blocks for operational success. Further research is needed to identify how our current training pipelines, manning requirements, and information systems will need to be reshaped to accommodate the technology innovation in the form of AVSs. Further study of the impact of autonomous systems on formal Navy mission sets, like Navy Tasks, should be conducted to identify the level of autonomy required for accomplishment of associated performance metrics and MOE. Concurrently, research and evaluation can determine how these metrics will be affected by teams of both manned and autonomous agents acting in a collaborative manner with one another. The organization needs new ways to measure performance.

Finally, and perhaps most importantly, the complicated ethical and legal dilemmas associated with machine automated employment of firepower within the warfighting environment need a great deal more thought and study. Even if human supervisory "influence" can be maintained, this prospect poses serious problems for the "human in the loop," especially given the speed with which this type of action might occur. Furthermore, the question of just how AVS employed in this manner impact our understanding of the laws of warfare needs detailed exploration. To be sure, there are already questions being raised about the nature of UAS used in precision strike roles against insurgent targets in the skies over Afghanistan. These questions are perhaps stemming from a realization of the next level of future technology development. The capability is coming; "we" had better be ready.

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